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On the Relationship Between Schottky Barrier Capacitance and Mixer Performance at Cryogenic Temperatures

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***Abstract*—The flat-band voltage is the Schottky junction voltage required to shrink the depletion width to zero. At cryogenic temperatures, mixer diodes are generally biased and/or pumped beyond the flat-band condition to minimize conversion loss and noise figure. This occurs despite the presumed sharp increase in junction capacitance near flat-band, which should instead limit mixer performance. Past moderate forward bias, the diode C–V relationship is difficult to measure. A simple analytic expression for $C(V)$ is usually used to model and predict mixer performance. This letter provides experimental data on $C(V)$ at 77 K based on a microwave measurement and modeling technique. Data is also provided on the conversion loss of a singly balanced mixer optimized for 77 K operation. The connection between junction capacitance, flat-band potential, and conversion loss is examined. It is shown that the analytic expression greatly overestimates the junction capacitance that occurs as flat-band is approached.**

I. Introduction

THE BENEFIT of cryogenic cooling to Schottky barrier mixer diodes is well known. Cooling the diode from 300 to 20 K reduces a mixer's noise temperature by at least a factor of two in the millimeter-wave frequency range [1]. It is also generally accepted that conversion loss is minimized only when the junction conductance variation swings over the junction conductance extremes [2]. But as the junction voltage approaches the flat-band potential and the junction resistance vanishes, the junction capacitance grows unbounded according to the analytic expression $C_j(V_j) = C_{j0}/(1-V_j/\phi_{bi})^{1/2}$. Here C_{j0} is the zero bias junction capacitance and ϕ_{bi} is the flat-band potential. This expression is based on an approximation that deteriorates as forward voltage approaches flat-band, yet it is widely used in mixer analysis. The interpretation of the metal–semiconductor interface model assumes that there is an abrupt transition from the depletion region to the undepleted semiconductor. In reality, the charge must be continuous and finite. So, the singularity is an artifact of the model. It was reported in [3] that the intrinsic conversion loss would become excessive at cryogenic temperatures, even though the cooled junction has a greater nonlinearity. This prediction is contrary to experiment, as has been the topic of recent work by Crowe and Mattauch [4], [5].

It was explained in [4] and [5] that although the junction capacitance theoretically becomes infinite at flat-band, junction capacitance exists only because charge is stored in the depletion layer. At the flat-band voltage, the depletion layer thickness is zero and the diode equivalent circuit should reduce to the series resistance. Their numerical model showed that the peak junction voltage must exceed the value corresponding to a situation in which the diode current exceeds the flat-band current. It was also shown that expectations of degraded intrinsic conversion loss upon cooling are overly pessimistic. Their model did assume that the junction capacitance behaved the same way, regardless of operating temperature.

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II. Capacitance Model

A more accurate model of the capacitance-voltage relationship was presented in [6]. This model was based on a numerical drift-diffusion approximation. The analysis predicted a much less dramatic rise in junction capacitance near flat-band and showed further consistency between theoretical and experimental mixer performance.

In this work, the impedance of a silicon Schottky diode was measured at 77 K. (The series resistance (r_s) was obtained by plotting the difference between the voltage from the measured log I–V curve and the closest-fitting straight line projected from the linear region, at several high current levels. The slope of the resulting straight line yielded an r_s of 5.7 Ω, which was essentially independent of temperature.) The device was bonded to a coplanar waveguide carrier mounted in a closed-cycle He refrigerator. The carrier was connected to a network analyzer via a coaxial cable. With no dc voltage applied, the parasitic reactances and C_{j0} were determined by tickling the diode with a −20-dBm signal. The forward voltage was then incrementally adjusted up to flat-band. De-embedded impedance data is shown in Fig. 1. The model's intrinsic parameters were then adjusted to match the measured S-parameters while the parasitic element values were held constant. (A beam lead inductance of 0.022 nH and a package capacitance of 0.020 pF were obtained.)

The modeled $C_j(V_j)$ data extracted from this experiment is shown in Fig. 2. Although it is conceivable that there is some excursion between the fourth and fifth data points, the salient features are that the capacitance increases more slowly than predicted and that $C_{j\,\max}$ occurs in advance of the flat-band potential. These experimental results are consistent with the analysis presented in [6].

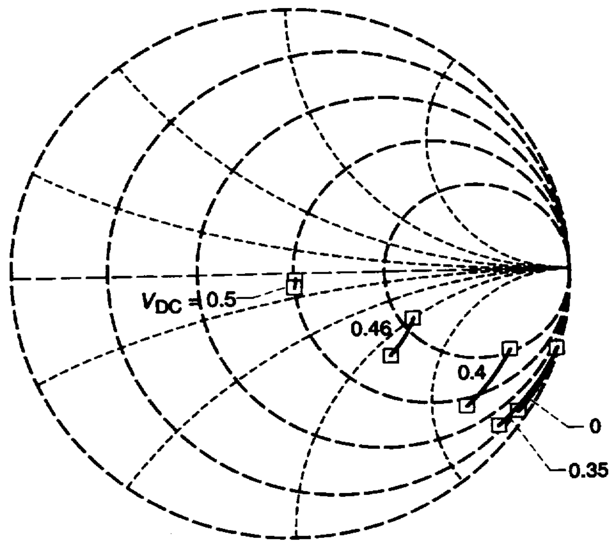

Fig. 1. De-embedded diode impedance data at 77 K as a function of dc bias with −20-dBm RF drive, RF = 5.0–10.0 GHz.

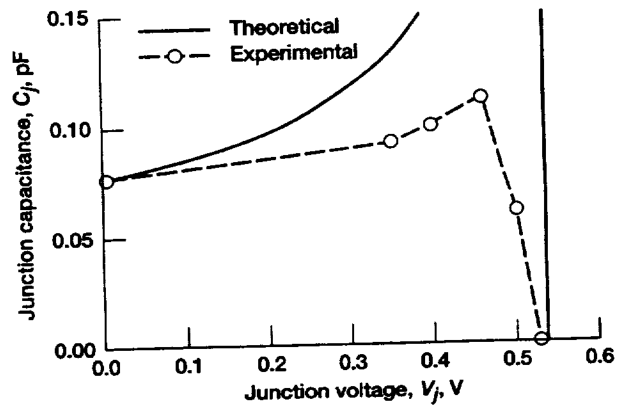

Fig. 2. Junction capacitance derived from RF measurements and theoretical curve from analytic expression.

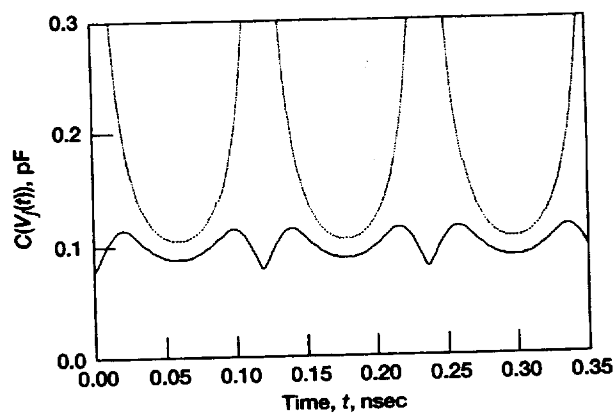

Fig. 3. Time-varying capacitance waveform based on experimental data (solid line) and analytic expression (dashed line). Maximum capacitance derived from the analytic expression was arbitrarily truncated at 10 C_{j0}.

III. Experimental Mixer Performance

An X-band mixer, based on the above device, was developed [7]. A signal matching circuit simultaneously provided a reactive termination to the image, sum, and first, second, and third local oscillator harmonic frequencies. The junction voltage was determined from measurements of the rectified current and knowledge of the diode terminations. It was shown that the peak instantaneous voltage clearly exceeded the voltage at which $C_{j\,\max}$ occurred and barely exceeded the flat-band voltage. The time-varying capacitance waveform $C_j[V_j(t)]$ was calculated based on the data of Fig. 2 and contrasted to the analytic expression. The results shown in Fig. 3 correspond to a +1-dBm LO drive level and a dc bias of 0.424 V. The average components are 0.098 and 1.771 pF for the experimental and analytical data, respectively. The mixer conversion loss was dissected into its intrinsic and parasitic parts and was found to agree extremely well with the minimum theoretical value. A conversion loss of 2.3 dB, which included IF filter, dc block, and hybrid coupler losses was measured at 7.2 GHz. This performance is very nearly equal to what one would expect from a nonlinear resistance with a classical exponential characteristic. Weinreb and Kerr [8] showed that to maintain a given conversion loss and impedance level with temperature (T), the LO power should be reduced in proportion to $(T/T')^2$, where T' corresponds to the lower temperature. However, they also showed that the dc bias voltage must increase accordingly, thereby increasing the mean junction capacitance by a factor proportional to $(T/T')^{1/2}$. Apparently, the total conversion loss should degrade since its lower limit, imposed by junction parasitics including C_j, is inversely proportional to the diode cutoff frequency.

IV. Conclusion

The inevitability of degradation in the conversion loss of diode mixers upon cryogenic cooling has long been debated. Evidence has been presented here to suggest that the junction capacitance departs from the monotonic behavior predicted by the usual analytic expression. The data supports a more realistic interpretation of the apparent $C_j(V_j)$ singularity. Results showed that the minimum conversion loss was obtained when the total bias clearly exceeded the bias at maximum junction capacitance and the flat-band voltage by about 5%. Clearly, the increased nonlinearity of a cooled diode can be used to an advantage, despite the presumed increase in mean junction capacitance upon cooling.

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